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OPTICAL DATA PROCESSING METHODS

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Two-dimensional image edge enhancement in the two-phonon diffraction

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Abstract. **We suggest using the two-phonon Bragg scattering regime for two-dimensional image edge enhancement by means of acousto-optic (AO) diffraction on a single sound wave. Image edge enhancement is demonstrated in the first diffraction order by using an AO cell made of the TeO_2 single crystal. To explain this effect, a three-dimensional model of AO interaction is proposed, which takes into account the angular selectivity of diffraction both in the plane of Bragg scattering and in the plane orthogonal to it.**

Keywords: *acousto-optic diffraction, Bragg regime, image edge enhancement.*

Optical methods of data processing have a number of unique possibilities, which are absent in digital methods in principle. For example, they allow one to perform a 'superfast' Fourier transform over large data arrays contained in images, the calculation rate of the Fourier image in an optical system being the same for any number of resolvable elements [1].

One of the important aims of optical data processing methods is the image edge enhancement, which makes it possible to decrease substantially the processed data arrays by retaining in this case the image parameters important for identification such as shape and dimensions [2]. Acousto-optic (AO) methods are widely used to solve the problem of image edge enhancement (see, for example, [3–5]). By its nature, the AO interaction is one-dimensional and because of this, the two-dimensional image edge enhancement seems impossible at first glance. However, variants of AO diffraction have been found, which provide the two-dimensional image edge enhancement by diffracting light on a single sound wave when using the tangent geometry [4–6] or collinear interaction [7]. In these variants the transfer function of diffraction is described by circumferences. The authors of paper [8] performed a complex study of the variants of Bragg scattering into two diffraction orders (zero and first), which are the most attractive for the problem of image processing, and presented the transfer function for these variants.

In this paper, we suggest using the two-phonon Bragg diffraction for the two-dimensional image edge enhancement, the image edge being enhanced in the first diffraction order. This variant is studied for the first time. The appearance of this method expands the possibilities of using the AO interaction in the image processing problems.

First, we will describe the experiment and present the experimental results. As a processed image, we used a rectangle in the form of a 1×1.5-mm slit illuminated from one side by a broadened beam from a 0.63-μm He–Ne laser. We processed the images using the Fourier method described in detail in papers [1, 9, 10]. In our experiments, the Fourier transform was performed by two lenses with identical focal lengths (f = 16 cm). The lenses were spaced by distance $2f$ from each other. The slit was located in front of the first lens at distance f. We placed between the lenses an AO cell filtering the spatial frequencies. A screen was placed behind the second lens at distance f. The AO cell was made of a TeO_2 single crystal to whose (110) face there was glued a $LiNbO_3$ piezoelectric transducer generating a transverse acoustic wave at a frequency of 35.5 MHz. The AO interaction length was 6 mm, and the transducer dimensions were 6×4 mm. A 'slow' wave propagated inside the crystal at 0.617×10^{-5} cm s^{-1}. Radiation was directed at a small angle to the optical axis of the crystal [001]. In this case, anisotropic two-phonon diffraction was realised in the crystal. When selecting the optimal high-frequency-signal voltage supplied to the transducer (5.0 V in our case), a two-dimensional image edge in the first diffraction order could be distinctly observed on the screen. Figure 1 presents the photograph of the diffraction orders obtained during diffraction of a rectangular image. One can see that in the first diffraction order we have a well-pronounced image edge of the rectangular slit of a rather good quality both in the vertical and horizontal directions.

a b

Figure 1. Photograph of a rectangular slit image in the zero diffraction order (a) and its edge obtained in the first diffraction order (b).

To analyse theoretically the obtained effect, we considered a three-dimensional model taking into account the angular detuning of Bragg scattering both in the diffraction plane and in the plane orthogonal to it. Figure 2 shows a three-dimensional vector diagram of two-phonon Bragg diffraction in a single-axis positive gyrotropic crystal, for example, in the TeO_2 crystal. Here, S_1 and S_2 are the wave-vector surfaces of ordinary and extraordinary rays, respectively. The Z axis

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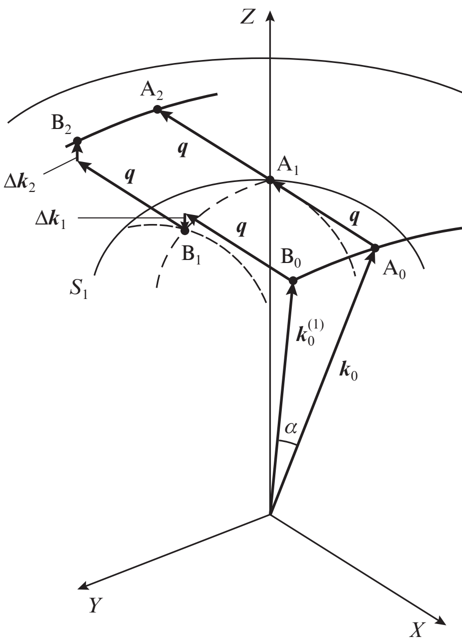

Figure 2. Three-dimensional diagram of two-phonon Bragg diffraction.

coincides with the optical axis of the crystal and the acoustic wave with the wave vector $\boldsymbol{q}$ is directed along the X axis. Let incident radiation with the wave vector $\boldsymbol{k}_0$ be directed to point A_0 lying at the intersection of the plane XZ and the surface S_2. As a result of the AO interaction with the acoustic wave $\boldsymbol{q}$, the ray $\boldsymbol{k}_0$ successively diffracts in the directions of the rays whose wave vectors are directed to points A_1 and A_2. Point A_1 lies on the surface S_1, while point A_2 lies on the surface S_2. Anisotropic diffraction of light on sound is studied. Both diffraction events occur in the regime of strict Bragg synchronism. If now the ray $\boldsymbol{k}_0$ is incident at an angle α to the plane XZ, i.e. propagates in the direction of the ray $\boldsymbol{k}_0^{(1)}$ directed to point B_0, it successively diffracts during the interaction with the same acoustic wave in the direction of the rays whose wave vectors are directed to points B_1 and B_2. However, diffraction events are accompanied in this case by Bragg synchronism detuning. The detuning vectors are denoted in Fig. 1 as $\Delta\boldsymbol{k}_1$ and $\Delta\boldsymbol{k}_2$.

We will consider the problem of two-phonon Bragg scattering in the plane-wave approximation. Then, the amplitudes C_0, C_1 and C_2 of the waves scattered in the zero, first, and second diffraction orders are related with each other by a system of differential equations [11]

$$\frac{dC_0}{dz} = -\frac{p}{2}C_1\exp(-i\Delta k_1 z),$$

$$\frac{dC_1}{dz} = \frac{p}{2}[C_0\exp(i\Delta k_1 z) - C_2\exp(i\Delta k_2 z)], \qquad (1)$$

$$\frac{dC_2}{dz} = \frac{p}{2}C_1\exp(i\Delta k_2 z),$$

where z is the coordinate along which the AO interaction occurs; $p = \nu/l$; ν is the Raman–Nath parameter depending on the sound wave power; l is the AO interaction length.

Analysis of system (1) shows that the best relation between the amplitudes C_0, C_1, C_2 is provided at $\Delta k_1 = \Delta k_2 = 0$. If Δk_1, Δk_2 are nonzero, the relation between the amplitudes becomes weaker. This leads to the AO interaction nonuniformity in the direction orthogonal to the diffraction plane, i.e. to the appearance of angular selectivity in this direction.

The specific values of $\Delta\boldsymbol{k}_1$ and Δk_2 were found from geometric constructions. We assumed that the wave-vector surfaces of a single-axis gyrotropic crystal are described by the expressions

$$\left(\frac{\lambda}{2\pi}\right)^2\left[\frac{x^2}{n_o^2} + \frac{y^2}{n_o^2} + z^2\left(\frac{1}{n_o^2} + G_{33}\right)\right] = 1,$$

$$\left(\frac{\lambda}{2\pi}\right)^2\left[\frac{x^2}{n_e^2} + \frac{y^2}{n_e^2} + z^2\left(\frac{1}{n_o^2} - G_{33}\right)\right] = 1, \qquad (2)$$

where λ is the wavelength of light in vacuum; n_0, n_e are the main refractive indices of the crystal; G_{33} is the gyration pseudotensor component.

Before the theoretical analysis, it is necessary to note that the experimental effect was observed at a rather high voltage supplied to the transducer (~ 5 V). For comparison, the maximum efficiency of the second-order Bragg diffraction of 'ordinary', non-diverging laser radiation was achieved at ~ 1 V. Based on this, we analysed theoretically the diffraction regimes realised at large Raman–Nath parameters ν, exceeding (at least, twice) the value $\pi\sqrt{2}$ corresponding to the complete transfer of optical non-diverging radiation into the second order.

Figure 3 presents the dependences of the modulus of the transfer function of the first diffraction order $|H_1|$ on the spatial frequency $k_x = (2\pi n_o/\lambda)\Delta\varphi$, where $\Delta\varphi$ is the angle of deflection of incident radiation from the direction of strict Bragg resonance. It was assumed that diffraction occurs in the plane XZ containing the optical axis Z, incident radiation being deflected in the ame plane. In calculations, $l = 0.6$ cm. The curves in Fig. 3 were plotted for different Raman–Nath parameters ν. One can see that the transfer function profiles $|H_1|$ change rather strongly by varying ν. Note that the curves were obtained in the plane-wave approximation. In considering real beams, the functions $|H_1|$ will be smoother. In particular, curve (*4*) near the maximal values will represent not a wavy line but a somewhat averaged curve. We will take it into account in the further analysis.

The next step is the search for the transfer function profiles formed in the planes XZ and XY and coinciding at the most with each other. Figure 4 demonstrates this variant. It presents the transfer functions of the first diffraction order

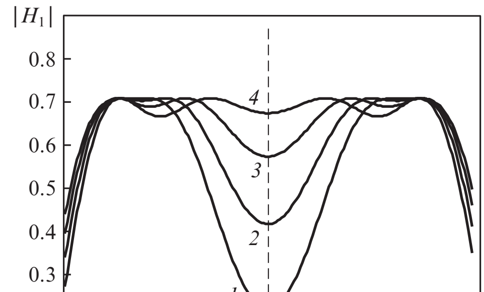

Figure 3. Dependence of $|H_1|$ on k_x at $\nu = 2.1\pi\sqrt{2}$ (*1*), $2.2\pi\sqrt{2}$ (*2*), $2.3\pi\sqrt{2}$ (*3*), and $2.4\pi\sqrt{2}$ (*4*) in the case of diffraction in the plane XZ.

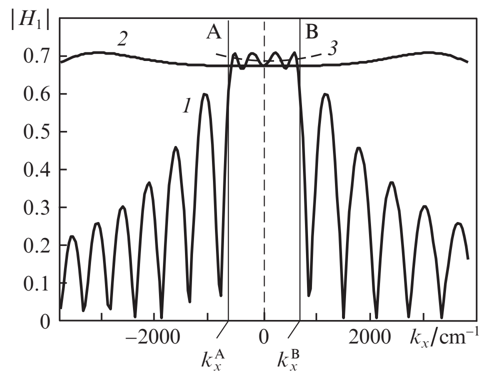

Figure 4. Dependence of $|H_1|$ on k_x at $\nu = 2.4\pi\sqrt{2}$ in the case of diffraction in the plane XZ (*1*) and (*2*). Curve (*3*) is curve (*1*) averaged in the region between the straight lines A and B; $k_x^{\mathrm{B,A}} = \pm 650$ cm^{-1}.

$|H_1|$ formed in the planes XZ and XY at $\nu = 2.4\pi\sqrt{2}$. The half-widths of these transfer functions differ by approximately ten times. However, in the range of the k_x values lying between the vertical straight lines A and B, curve (*2*) virtually repeats curve (*3*) obtained by averaging curve (*1*) in this range. This means that this range is suitable for obtaining the two-dimensional optical image edge because the derivatives of curves (*2*) and (*3*) in the most of this range are nonzero.

Therefore, this paper presents the first results of the image contouring with the help of two-phonon Bragg diffraction. We have demonstrated the experimental results, presented the tree-dimensional model making it possible to trace conveniently the two-phonon scattering of radiation in an anisotropic gyrotropic medium and to understand the mechanism of two-dimensional image contouring. We have analysed within this model the transfer functions explaining the possibility of two-dimensional image contouring.

The presented model describes the experimental results only qualitatively but does not describe some peculiarities observed in the experiment. A more detailed theoretical and experimental study of this variant of image contouring is planned elsewhere.

Based on the above said, we can state the main results of this paper:

(i) Two-phonon Bragg diffraction is suggested so that the two-dimensional edge image be enhanced with the help of the AO diffraction on a single sound wave.

(ii) Image edge enhancement is demonstrated in the first diffraction order by using the Fourier processing of an optical image, where the AO cell made of the TeO_2 single crystal served as a filter of spatial frequencies.

(iii) We have found that the transfer function of the first diffraction order depends on the acoustic power, the AO interaction length, and the characteristics of the AO cell material.

(iv) We have shown that by selecting the sound power, we can obtain the two-dimensional transfer function of the first diffraction order whose profile formed in the diffraction plane coincides at the most with its profile in the orthogonal plane.

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References

1. Stark H. (Ed.) *Application of Optical Fourier Transforms* (New York: Acad. Press, 1982; Moscow: Radio i svyaz', 1988).
2. *Handbook of Pattern Recognition and Image Processing.* Ed. by T.Y. Young, K.-S. Fu (New York: Acad. Press, 1986).
3. Athale R.A., van der Gracht J., Prather D.W., Mait J.N. *Appl. Opt.*, **4**, 276 (1995).
4. Babkina T.M., Voloshinov V.B. *J. Opt. A: Pure Appl. Opt.*, **3**, S54 (2001).
5. Balakshy V.I., Voloshinov V.B. *Kvantovaya Elektron.*, **35**, 85 (2005) [*Quantum Electron.*, **35**, 85 (2005)].
6. Balakshy V.I., Voloshinov V.B., Babkina T.M., Kostyuk D.E. *J. Mod. Opt.*, **52**, 1 (2005).
7. Balakshy V.I., Mantsevich S.N. *Opt. Spektrosk.*, **103**, 831 (2007).
8. Balakshy V.I., Kostyuk D.E. *Appl. Opt.*, **48**, C24 (2009).
9. Kotov V.M., Shkerdin G.N., Shkerdin D.G., Voronko A.I., et al. *Opt. Zh.*, 74 (2), 12 (2007).
10. Francis T.S.Yu., Iam-Choon Khoo. *Principles of Optical Engineering* (New York: John Willey & Sons, 1990).
11. Balakshy V.I., Parygin V.N., Chirkov L.E. *Fizicheskie osnovy akustooptiki* (Physical Foundations of Acousto-optics) (Moscow: Radio i svyaz', 1985).